Monolithic Source of Photon Pairs

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The creation of monolithically integratable sources of single and entangled photons is a top research priority with formidable challenges: The production, manipulation, and measurement of the photons should all occur in the same material platform, thereby fostering stability and scalability. Here we demonstrate efficient photon pair production in a semiconductor platform, gallium arsenide. Our results show type-I spontaneous parametric down-conversion of laser light from a 2.2 mm long Bragg-reflection waveguide, and we estimate its internal pair production efficiency to be 2.0×10^{-8} (pairs/pump photon). This is the first time that significant pair production has been demonstrated in a structure that can be electrically self-pumped and which can form the basis for passive optical circuitry, bringing us markedly closer to complete integration of quantum optical technologies.

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There exist few experiments in the rapidly growing field of quantum information science that do not profit from the use of photon pairs. They are used ubiquitously as Einstein-Podolsky-Rosen sources in experiments that probe the fundamentals of quantum mechanics [1,2]. They can be used to improve the security of communication [3] and are an integral part of proposals for optical quantum computers [4]. Yet, the current technology for creating photon pairs, largely based on nonlinear optical processes, puts many exciting experiments out of reach. This is because photon pair sources are dim and physically large and cannot be integrated with either their pump lasers or the rest of the experiment.

In this Letter, we present new experimental results demonstrating efficient photon pair production from a gallium arsenide (GaAs)-based integratable waveguide structure called the Bragg-reflection waveguide (BRW). Because electrical pumping has been demonstrated for very similar structures, it holds great potential to be truly monolithic and thus to vastly improve the scalability of photonic quantum information technology.

The main contributing factor behind the current *lack* of scalability is that, to date, the components of photonic quantum information technology have been developed independently. Semiconductor lasers comprise the primary light sources; nonlinear optical processes in bulk crystals or in waveguides provide the nonclassical light [5,6]; dielectric or glass chips host integrated waveguide quantum photonic circuits [7–9]; semi- and superconductor or up-conversion-based detectors read the circuit outputs [10–12]. As none of these components exist in the same monolithic platform, stability and scalability continue to plague larger and more complicated experiments.

GaAs and its material derivatives present a strong case for monolithicity, because it can support both the primary light source and dielectric waveguide circuitry. Additionally, for photon pair production via spontaneous parametric down-conversion (SPDC), the GaAs-based material system affords a very large nonlinearity. However, facilitating SPDC in this platform has historically been challenging. This is because GaAs lacks any natural ability to phase match the interacting waves. A variety of solutions have been proposed [13–18]; moreover, improvements in their technology have allowed successful demonstrations of parametric down-conversion [19,20], but in all cases, the proposed phase-matching solutions are in discord with the fabrication of an on-chip light source.

Recent advances in phase matching [21] have shown that the BRW is a very promising candidate for a monolithic source of photon pairs. BRWs achieve confinement and guidance of waves in a core layer via two methods: total internal reflection and Bragg reflection. Respectively, they sustain two different types of eigenmodes—total internal reflection modes that are guided by the higher effective index of the core region and Bragg modes whose effective index can be smaller than the refractive indices of the host materials.

Phase matching between these two types of modes has recently been demonstrated; in particular, second-harmonic generation [22] has been observed for three different combinations of the interacting waves: type-0, type-I, and type-II. Lithographically defined, BRWs can be made compact and alignment-free with ultimately low development costs. The result presented here—demonstrating practical pair production for the first

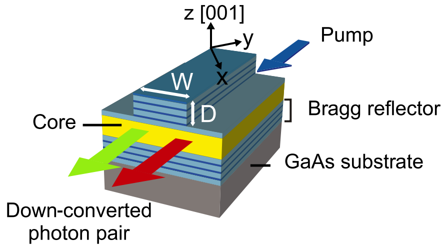

FIG. 1 (color online). Device geometry: A schematic of a ridge Bragg-reflection waveguide as an integrated source of quantum light. The waveguide core layer (yellow) supports index-guided light as well as light confined by the transverse Bragg reflectors (alternating light and dark blue layers). The Bragg layer thicknesses and material composition along with the width (W) and the ridge height (D) are design parameters that determine the wavelengths at which photon pairs can be created. Pump photons (represented by the blue arrow) are injected into the structure and photon pairs (represented by the red and green arrow, respectively) emerge at the output facet. The structure is grown on a [001]-GaAs substrate (dark gray).

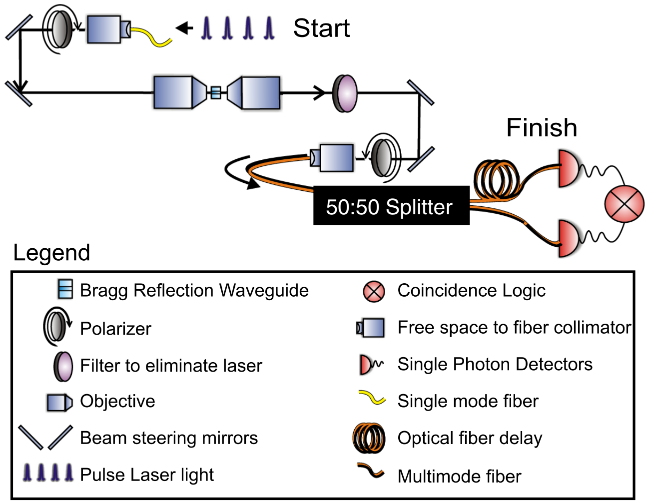

FIG. 2 (color online). The SPDC experiment: TM polarized picosecond pulses of light near a wavelength of 775 nm were injected into the waveguide. Light emitting from the waveguide was color filtered to remove the pulsed input. What remained was split probabilistically before being sent to two single photon detectors. The path to one of the detectors was optically delayed by 60 ns to allow it to be conditionally armed upon the detection of the earlier photon at the other detector. Time differences between (detection events at) the two detectors were recorded, and a histogram of all recurring time differences was created.

time—shows that BRWs are realizing their potential as a low-power, electrically injected source of photon pairs.

Established via second-harmonic generation type experiments, the 4.4 μm wide, 2.2 mm long BRW that was studied facilitated type-I phase matching between a transverse magnetic (TM) Bragg mode ($\lambda \approx 775$ nm) and a transverse electric (TE) fundamental mode ($\lambda \approx 1550$ nm). Details of its design can be found in the literature [22], and a schematic representation of the device is illustrated in Fig. 1. By using these parameters as a guide, the ability of the BRW to mediate photon pair production was investigated by exciting the Bragg mode with TM polarized light at 775 nm and studying any TE fundamental light produced in the vicinity of 1550 nm for photon pairs. This was accomplished by splitting the produced light into two paths, directing each path onto a single photon detector, and looking for time correlations between detection events. For the study, laser pulses with a duration of approximately 2 ps were injected into the BRW at a rate of 76 MHz. Average powers before the front facet ranged anywhere from 1 to 20 mW. Light emerging from the opposite end of the BRW was color filtered to remove the input pulses, and the delay time (τ) between detection events at each detector was recorded. This allowed an inference of whether or not the two detectors tended to click in coincidence—a hallmark signature of SPDC. The experiment is reminiscent of the Hanbury Brown–Twiss [23] experiment and effectively probes the photon pair correlation function $g^{(2)}(\tau)$, representing the conditional probability to detect a second photon at a time τ after a first photon detection.

To perform the experiment, we constructed an "end-fire rig" allowing precise positioning of both the waveguide and coupling optics. The physical setup is shown in Fig. 2. On the input side, it consisted of two steering mirrors to direct light through a high numerical aperture (N.A. = 0.95) 100× objective focused onto the front facet of the BRW. In fact, no specific provisions for coupling to the Bragg mode were taken, the only mode shaping occurring immediately before entering the setup via a short section of single mode fiber. An antireflection-coated 56× single aspheric lens focused onto the back facet of the BRW collected and collimated the output light. By using two additional steering mirrors and an antireflection-coated lens, the output light was refocused into the input fiber of a 3-port (1:2) multimode fiber beam splitter. The two output fibers were each directly connected to single photon detectors. The first detector was electronically armed and synchronized with every 40th pump laser pulse. A single photon detection in this detector started the time to amplitude converter (TAC) of a Becker & Hickl SPC-132 time-correlated single photon counter and armed the second detector. To compensate for the time required to electronically arm the second detector, an optical delay of ≈ 60 ns was introduced before the second detector. A detection event at the second detector stopped the TAC. As mentioned above, the time duration τ between starting and stopping the TAC was recorded. The various τ were placed into bins of size determined by the measurement jitter, and histograms of the frequency of recurrence of all τ were created. Examples are shown in Fig. 3.

Renormalizing to account for all optical and electrical delays, the data in Fig. 3(a) show a marked tendency for both single photon detectors to click in unison ($\tau = 0$)

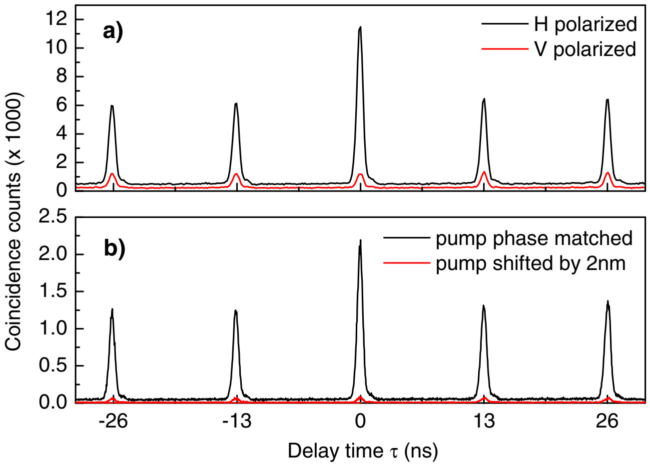

FIG. 3 (color online). Coincidence measurements: A peak at $\tau = 0$ indicates that both detectors responded in coincidence. The top figure (a) shows the effect of rotating a polarizer from TE (black) to TM (red) in the output while injecting TM polarized light on resonance with the phase-matching wavelength into the BRW. The bottom figure (b) shows the typical effect found when injecting light at (black) and away from (red) the resonant phase-matching wavelength. Peak widths are essentially determined by the finite detector time resolution of approximately 1 ns. The periodic signal on either side of the zero delay time is predominantly a result of pairs being produced in pulses preceding or succeeding the true coincidence pulse. The signal between the peaks is due to background light, detector dark counts, or (slowly decaying) fluorescence, thought to arise from deep level impurities in the sample.

when observing TE polarized light. Since light with a wavelength less than approximately 1400 nm was blocked, this is a strong indication that the BRW was producing more than one TE polarized photon per pulse between this lower limit and the detector cutoff of about 1700 nm. To verify the phase-matching criteria, we performed two tests independently—we tuned the input wavelength away from the vicinity of 775 nm and blocked the TE component in the output—both resulting in the disappearance of the coincidence response. As a final test of SPDC, it is known that for low input power the number of created photon pairs per pulse scales linearly with that power. Cross pulse coincidences, between different pulses, scale quadratically. We investigated this predicted linearity of the cross pulse to coincidence ratio by varying the input power. The results are shown in Fig. 4. All of this evidence strongly suggests that the BRW was producing photon pairs via type-I phase-matched SPDC.

To arrive at an internal conversion efficiency for the data presented in Fig. 3(a), it is necessary to know both the number of photons in the Bragg mode and the number of SPDC photons produced in the fundamental mode at some point along the waveguide. To determine this point requires knowledge of both the Bragg and fundamental mode losses along the waveguide. Because the Bragg mode loss is difficult to measure, we rely on previous results from work on similar structures [24] where, typically, Bragg mode propagation losses are 1 order of magnitude worse than those found for the fundamental mode. For the device used herein, we measured a linear loss coefficient of $\approx 4.3/\text{cm}$ for the fundamental mode by using the Fabry-Pérot method. For the 2.2 mm waveguide, this implies a transmission of about 40%. To achieve a 4% transmission for the Bragg mode, a linear loss coefficient of $\approx 14.8/\text{cm}$ for the Bragg mode is assumed. From this information, we calculate that the average compound Bragg mode and fundamental SPDC loss occurs at around 0.8 mm along the guide from the input facet. All relevant losses can now be assessed for the data in Fig. 3(a). To begin, it is estimated that the average pump power directly before the input facet was ≈ 14 mW. By using a plane wave model for the facet transmission ($\approx 73\%$), the power inside the waveguide lowers to 10.2 mW. Numerical calculations yield that about 10% of this light is actually coupled to the Bragg mode. Bragg mode transmission loss then dictates that there is about 317 μW of pump power available for down-conversion. Beyond the conversion point, we use similar methods to estimate the average SPDC photon transmission probability by accounting for fundamental mode loss, system loss and outcoupling (a combined total of 22%), the 1:2 fiber beam splitter (43%), and the individual detector efficiency (10%).

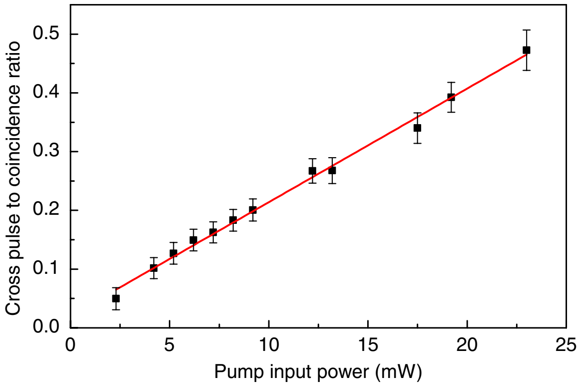

FIG. 4 (color online). Cross pulse to coincidence ratio: A demonstration of the dependence of the cross pulse coincidences to true coincidence ratio on the input power. Ignoring random events, the cross pulse signal is an indication of the pair per pulse probability (p_{pulse}) which, as shown here, increases linearly with laser power. This linear scaling of p_{pulse} builds the case that the signals we see originate from a pair production process like SPDC. By taking the ratio, system losses are largely eliminated.

We now make an assessment of the internal SPDC efficiency as follows: From the data in Fig. 3(a), the area under the red (bottom) curve is subtracted from the area under the black (top) curve for the zero delay pulse. This gives the net coincidence count (116 080), the rate being found by dividing this number by the duration over which the data were collected (900 s). Thus, from the detector's point of view, the BRW produced pairs at a rate of 129 counts/s. By incorporating the fundamental mode and system loss parameters, this implies that approximately 256 360 pairs/s exited the waveguide and that the waveguide created 643 000 pairs/s at the conversion point. As the single photon detectors were synchronized with approximately one out of every 40th laser pulse, i.e., at 1.9 MHz, we calculate that SPDC occurred with a probability of ≈ 0.36 pairs/pulse. Since the power in the Bragg mode is calculated to be about 317 μW at this point, we infer an SPDC efficiency of approximately 2.1×10^{-8} (pairs/pump photon). In other units, this is about 8.57×10^{7} (pairs/s)/mW of pump power in the pump mode at the point of conversion.

The above experimental efficiency estimate is just 1 order of magnitude away from the theoretical value obtained when applying a simplified version of formalism developed specifically for SPDC in waveguides [25]. Using 50/100 pm/V as, respectively, the effective second-order nonlinear susceptibility coefficient for AlGaAs/GaAs, along with the relevant mode profiles calculated with a commercial mode solver (Lumerical, Inc., Mode Solutions), we obtain an internal conversion efficiency of approximately 1.14×10^{-9} for the type-I SPDC process. The most likely reasons for the discrepancy are the difficulty in assessing the pump-to-Bragg mode coupling efficiency and in determining the loss of the Bragg mode in the waveguide. Additionally, very conservative estimates of the susceptibility coefficients have been used in the calculation in order to avoid overestimating the efficiency.

Integratable photon pair sources have been in existence for some time. Indeed, over the past decade, there have been numerous accounts of down-conversion from semiconductor-based solutions born out of various effective methods for phase matching. As an example, the latest SPDC efficiency reported for AlGaAs-based cavity-enhanced counterpropagating photons is approximately 10^{-11} per pump photon [20]. What sets the BRW platform apart is that it is readily capable of accommodating the monolithic integration of many different types of active and passive componentry. An example of this is the ability of the BRW to actively produce the classical light required for SPDC. In contrast, all other integratable phase-matching solutions have yet to show this possibility of being electrically injectable. At the moment, they function as externally pumped sources of nonclassical light—the photons they produce being not yet sufficient for practical use. Thus, as evidenced by their lack of widespread use in multiphoton (more than one pair) experiments pertaining to quantum information science, they continue to compete with more mature source materials like potassium titanyl phosphate, barium borate, or lithium niobate. Notably, the BRW source reported here is also insufficient to partake in these types of experiments. In order for it to do so, future designs must overcome the rather significant propagation loss factors. However, from an integrated standpoint, the ability of the BRW to be self-pumped is a very distinct advantage over the other sources.

Finally, being a waveguide, the BRW platform offers the capability to implement quantum circuitry. Although this has yet to be achieved, recent experimental demonstrations of quantum computational primitives using waveguide-based photonic circuits abound. The controlled NOT gate [7,9], phase control in integrated cross couplers [26], Shor's algorithm [27], and quantum walking [8,28] are among the highlights. Thus, circuitry based on the BRW architecture has a wealth of related research upon which to build.

The BRW thus emerges as an extremely attractive multifunctional platform on which to perform scalable photonics-based quantum computation. Furthermore, from a source perspective, BRWs are capable of actively producing photon pairs. As such, they have the potential to not only outperform the incumbent sources but to do so at considerably less expense and with a markedly smaller footprint. As practical semiconductor sources will inevitably be realized, the future looks very bright for the Bragg-reflection waveguide and photonic experiments in quantum information.

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